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A Real-Time Vision System to Monitor/Analyze the Changes in Composite Specimens During Mechanical Testing

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Research has demonstrated the feasibility of using digital image processing techniques to determine dimensional changes and analyze qualitative and quantitative fracture processes in fiber-reinforced composite material test specimens that have experienced environmentally and mechanically induced stresses. The application of image analysis techniques during mechanical testing has been shown to facilitate test automation and to provide information essential to interpretation and quantification of mechanical test data. Since fracture is a dynamic process, real-time image acquisition and special image processing techniques are needed to determine specimen size and shape changes, identify where fracture is initiated, and describe how fracture develops in specimens during mechanical testing. Images must be classified and interpreted in terms of appropriate fracture models to facilitate the analysis of mechanical test data and provide a quantitative assessment of damage.

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Contents

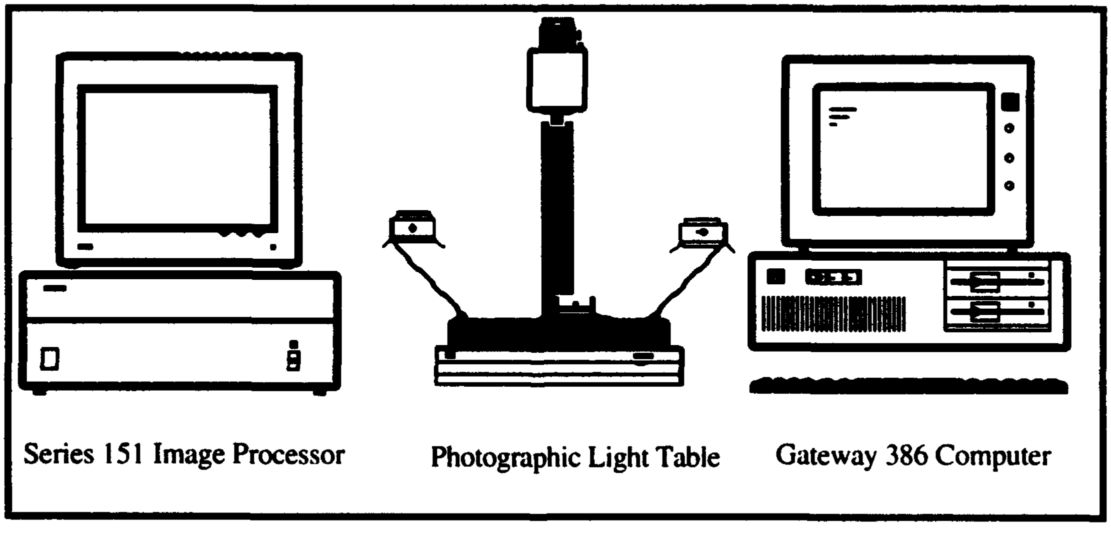
Figures

Tables

Introduction: This report describes the development and application of digital image analysis (DIA) techniques for analyzing the fracture behavior and environmental deterioration of test specimens prepared from fiber-reinforced polymer matrix composite materials. Digital image analysis techniques were employed to investigate the effects of moisture and temperature on the environmental aging of composite materials. A first generation digital image processing system developed at the Army Research Laboratory has been implemented to capture images which document the time sequence of damage accumulation and structural changes that occur during the environmental exposure and mechanical testing of polymer matrix composite materials. A more advanced system is currently being developed in collaboration with Quest Integrated, Inc. under an SBIR program sponsored by the Army Research Laboratory. The Quest system will have expanded digital image capturing and processing capabilities, as well as provisions for high speed, in-situ image acquisition and analysis of specimens undergoing deformation and fracture during mechanical testing. These techniques provide a nondestructive method for evaluating environmental deterioration and offer an innovative and versatile capability for more accurately analyzing the failure behavior of complex materials and structures. Digital image analysis complements other techniques for characterizing the physical and mechanical properties needed to guide the application and design of advanced composite materials.

Experimental Approach:
First Generation Testing And Image Processing System: An imaging system consisting of a CCD RS-170 video camera and a Series 151 Image Processor (Imaging Technology, Woburn, MA) under control of a Gateway 33 MHz 386 computer was used to analyze polymer matrix composite test specimens in two ways (see figure 1). The first was to record and characterize the effects of accelerated aging on the test specimens while the second was to identify and quantify the extent of damage as a result of mechanical testing. Special routines were developed using the image processor's C-interpreter for generating pixel histograms to help evaluate the digitized images.

Figure 1. Imaging System Configuration



The laminates used in this study were prepared from unidirectional S2-glass fiber, epoxy resin (SP250) prepreg materials (3M Corporation). The laminates consisted of 6 plies of prepreg in 4 different layup configurations. Defining lamina orientation as the angle (degrees) between the prepreg fiber direction and a reference axis (the X-axis, or flexural test specimen long axis, which is perpendicular to the load exerted during the 3-point bend test), the laminates are designated -

0^o	fiber orientation		$[0_6]_T$
60^o	"	"	$[60_6]_T$
$+-45^o$	"	"	$[+45_2 -45_2 +45_2]_T$
$0/90^o$	"	"	$[90_2\, 0_2\, 90_2]_T$

Flexural test specimens (nominally, 100 mm long x 19.3 mm wide x 1.45 mm thick) were carefully machined from the laminate materials and conditioned by drying at 60^o under vacuum for 5 days. Test specimens were immersed in distilled water at 80^o C for 144 hours to accelerate environmental aging. The percentage of moisture uptake was determined by measuring the change in specimen weight before and after immersion. Upon cooling to room temperature, wet specimens were blotted with filter paper and immediately weighed. After immersion and weighing, the specimens were dried under vacuum at 60^o C for at least 5 days or until all traces of moisture were removed. The conditioned specimens were then stored in a desiccator. Using the image processor, histogram analysis was carried out to quantify the effects of the accelerated aging process, by comparing the pixel count distributions of the aged specimens with that of the control specimens.

An automated Instron Universal Testing Instrument (Instron Corp., Canton, MA), was used for performing three-point loading, flexural tests. [1] The mechanical testing work cell includes the Instron (Model 4206) with hydraulic grippers and load cells selected for flexural testing of polymer matrix composite materials, a Zymate robot arm and controller (Zymark Corp., Hopkinton, MA), specimen racks, a bar code reader and a Gateway 386 computer. The robot is programmed to automatically transfer test specimens from the specimen racks to the test apparatus and then to remove specimens from the apparatus after the test is completed. All data acquisition, handling and reporting is fully automated. Stress was applied to fracture the specimens; however the strain was limited to prevent specimens from breaking apart. Recognizing that the location of the fracture damage region is well defined by the flexural test procedure, image acquisition and analysis was generally limited to a 19 mm region surrounding the area of probable damage. A histogram equalization function was used to enhance the contrast of the damaged region in each test specimen. Realizing that the image consists of 256 shades of gray, it was expected that most shades would fall away from the very dark (black) regions and the very light (white) regions. The damage regions, in fact, were only a slightly lighter shade of gray than the undamaged regions. The histogram equalization function equalizes the brightness of the entire image based upon the area of interest. It then uses LUTs (Look Up Tables) to force a normal distribution onto the area specified. This has the effect of greatly enhancing the contrast of the area of interest. A stretch frame function was used to finalize the area to be calculated. Similar to the histogram equalization function, the stretch frame function forces a distribution of gray levels onto a range of values.

1. ASTM D790 in Annual Book of ASTM Standards, 08.01, Philadelphia, PA: American Society for Testing and Materials, 1987.

Specifically, the range of gray values from 150 to 175 was chosen for this application. All values below 150 were turned to zero (black), and any value above 175 was equated to 255 (white). The stretch frame made the contrast sharper, by turning the fractured region white and the unfractured region black. Thus the only part of the image remaining was the fracture region which appeared on the monitor as sharp white in a field of black. Finding the extent of damage in the fractured region was relatively simple. The remaining white pixels were counted by the image processor and the fractional or percentage of damage could then be calculated.

Second Generation Testing and Image Processing System: An second generation in situ imaging system to acquire, interpret and archive images of composite materials during flexural testing is under development. The system will include a digital camera subsystem capable of capturing images over a 10-cm by 2.5-cm test section with 40 micron resolution. This capability will be provided by a conventional digital camera configured as either a camera array or a single camera on a translation stage. The resulting stream of image data will be captured by a frame grabber equipped with a 128MB RAM buffer. Up to 80 images will be captured and analyzed during a typical 250 second test. The maximum acquisition rate in burst sampling mode will be at least 30 frames/sec.

Image data will be analyzed using a multi-processor plug-in board on a desktop computer. Historically, it has been impossible to obtain the power required for high performance image interpretation on a desktop machine. However, the emergence of high speed buses, multitasking operating systems and multi-processor DSP and RISC based coprocessors has made it possible to consider the desktop computer as an alternative. These platforms represent the best price/performance value which is a prime consideration for commercial applications.
The emphasis of this program is on rapid image interpretation. Specifically, image interpretation which leads to an understanding of the failure dynamics in composite materials. The goals of the interpretation process are to:

- Determine specimen size and shape change.
- Locate the region(s) where mechanical failure is initiated.
- Define fracture type.
- Identify the sequence of damage accumulation and structural change.

Case Studies:
Aging/Life Prediction Study: For this study insuring that image processing conditions and test procedures remain constant was essential for obtaining reproducible results. The digital image analysis of wet specimens was very sensitive to the time interval between sampling and imaging and did not show the large shift in gray level values observed for aged specimens that were conditioned (dried). Excellent reproducibility was obtained when specimens were conditioned and maintained in the dry state. Digital image analysis of conditioned specimens aged under identical conditions and stored in a desiccator generated similar pixel histograms. Fiber orientation, relative to the camera position, however, did not significantly affect the average gray level values of aged and unaged specimens. Specimens could be rotated 90^{o} for image analysis with little effect on pixel count distribution under the prescribed test conditions. Image analysis was performed after the aged specimens were conditioned (dried at 60^{o}C). Histogram analysis shows that the pixel count distribution of aged specimens was shifted to higher gray level values when compared to that of the control specimens. The calculated mean weighted average gray level for control and aged (144 h) specimens are listed in

Table 1. The average gray level values for the control specimens are 160.5-161.9 compared with 188.7-191.0 for the aged specimens.

Table 1. Damage Area, Mean Gray Level and Percentage Moisture Uptake

Specimen	Mean Gray Control	Mean Gray Aged (144 Hrs.)	Moisture Uptake (weight-%)	% Damage (Unaged)
0^o	160.5	191.0	2.82	90
60^o	161.9	188.7	2.90	13
$+45^o$	161.1	189.4	2.98	38
$0/90^o$	161.9	188.7	2.70	20

As mentioned in the experimental section, the ASTM D790 method was performed. A support span of 25.4 mm (1 inch) was chosen because of the specimen thickness. The crosshead speed and temperature were 0.100 in/min and 25°C, respectively. Flexural modulus, flexural strength and the maximum load at yield were determined. The extent of fracture (% Damage) as indicated by digital image analysis was essentially identical for unaged and aged specimens with the same fiber orientation. It was also shown that the specimens have a distinctive fracture pattern based on fiber layup and test orientation. The fracture direction parallels the lamina fiber orientation direction and the fracture patterns are highly reproducible. The damage mode in the unaged specimens is a combination of delamination and fiber separation within plies. Pixel analysis of white/gray versus black regions shows that the percentage white/gray pixels (apparent percent damage) is greatest for the 0^o specimen and least for the 60^o specimen (Table 1).

Flexural test results for conditioned (dry) laminate specimens before and after accelerated aging are summarized in Table 2. In general, immersion of test specimens in water at 80°C for 144 hours caused a reduction of 10-30% in their flexural properties. As expected, fiber orientation has a significant effect on mechanical properties. However, the relative changes in flexural properties with accelerated aging were not significantly affected by fiber orientation. This study showed that accelerated aging of the SP250 epoxy/glass fiber test specimens in water at 80^o C for 144 hours is comparable to environmental exposure results for the same material under tropical rain forest conditions for five to ten years.

Table 2. ASTM 0790 Flexural Test - SP250 Laminates

Specimen		Modulus (MPa)	Strength (MPa)	Max. Load (kN)
0^o	control	32,800	1,440	1.69
	aged (144h)	29,700	1,046	1.36
60^o	control	14,700	376	0.475
	aged (144h)	10,200	345	0.461
45^o	control	7,320	299	0.339
	aged (144h)	5,290	240	0.303
$0/90^o$	control	1,520	280	0.294
	aged (144h)	1,170	211	0.253

Table 1 shows that aged test specimens were all found to have similar percentages of moisture uptake. Thus, fiber orientation does not seem to affect moisture absorption. This is consistent with the fact that water absorption is a matrix dominated property and infers that, except for fiber orientation, resin-fiber interface characteristics of the specimens are essentially identical.

Carbon-Fiber Composite Study: In preliminary experimental studies, It was demonstrated that in situ images could be analyzed to locate and identify the formation of damage in carbon-fiber composite material. During these experiments, a $\pm 45^{o}$ AS4/3501-6 carbon/epoxy test specimen was subjected to a flexural load which resulted in the formulation of micro cracks along the specimen's surface and edge. An image of this specimen is shown in Figure 2.

In this image, the matrix cracks appear as long, thin white lines. This image also includes a variety of other surface features including ink markings and scratches which are typical of unprepared test specimen surfaces. The objective of the image analysis operation was to separate the useful image data (matrix cracks) from the image noise (scratches and ink markings) and obtain the distribution of matrix cracks.

To accomplish this objective a morphology based algorithm was developed to process the image. This algorithm is based on the application of a "structure element". The structuring element is used to decompose the image into those features that match the expected size and shape of the matrix cracks. In many composite material testing applications it is possible to predict the general shape and orientation of localized damage phenomenon such as matrix cracking based on the ply configuration and test type. Consequently, morphology based image analysis provides a powerful tool to isolated damage modes. Figure 3 provides an example of the results obtained using the algorithm on the image from Figure 2.

Interpretation of Matrix Crack Damage in a Carbon Fiber Flexural Test Specimen.

Figure 2. Original Image $\pm 45^{o}$ AS4/3501-6 Carbon/Epoxy Specimen

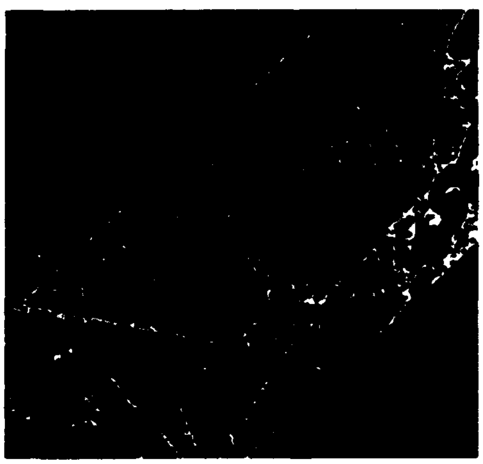
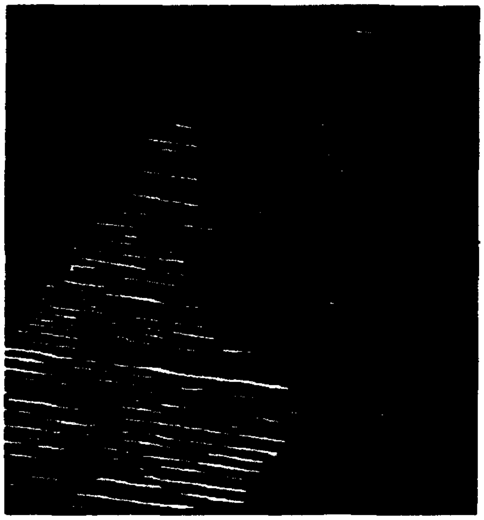


Figure 3. Microcrack Shapes Extracted From Figure 2 Using Morphology Based Image Processing Algorithm



The extension of this technique to streams of in situ image data would make it possible to obtain the following relationships:

- Crack length vs. location.
- Distribution of fractures per unit length.
- Distribution of crack separation distance.
- Distribution of fracture size and shape.
- Rate of fracture generation per applied load.
- Rate of fracture size and shape change per applied load and/or per location.
- Fiber rotation per applied load.

Conclusions and Recommendations: Digital image processing technology was employed to capture and analyze images of aged and unaged composite test specimens before and after fracture. The digitized images were evaluated using pixel histograms generated through routines developed on a C-interpreter. Pixel histograms of environmentally aged test specimens were broader and shifted to higher gray level values compared to histograms of the unaged specimens. Under the test procedures developed, DIA results were reproducible and fiber orientation did not significantly affect the average gray level values of either aged or unaged specimens. Laminate fiber orientation and aging conditions were found to have a significant effect on the observed fracture patterns and surface characteristics of the test specimens after fracture. Digital image processing is a promising technique for investigating the fracture and aging behavior of composite materials. Digital image processing can provide reliable and quantitative information relating to visual changes induced in composite test specimens due to accelerated environmental aging. Additional studies are required to improve analytical procedures for describing and quantifying fracture characteristics of flexural test specimens and to understand how and why environmental aging affects changes in pixel histograms. A detailed systematic study to determine possible correlation's between DIA and results obtained from mechanical, physical and chemical characterization of composite test specimens as a function of environmental aging conditions is needed. In addition possible application of this technology to other types of materials should be investigated.

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